# THMC instabilities in high temperature/pressure diagenesis of shale gas reservoirs

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Never Stand Still

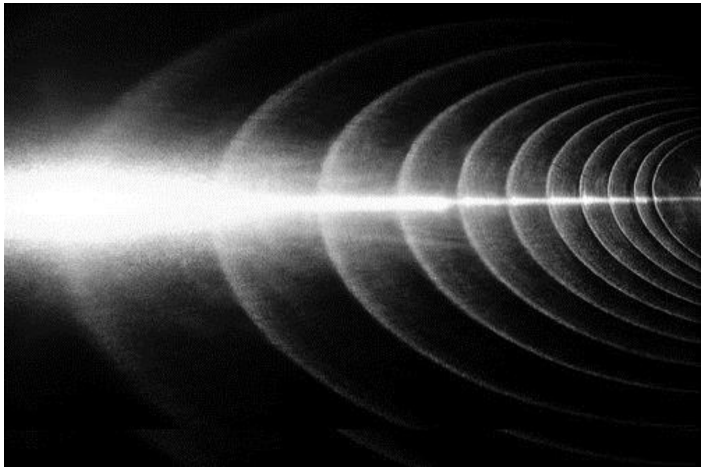
School of Petroleum Engineering

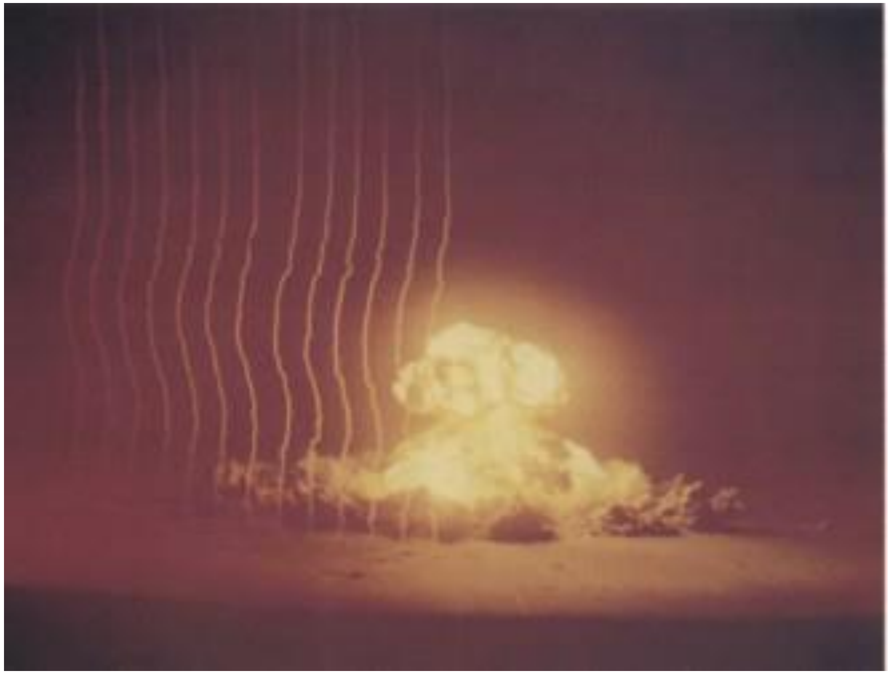
# Overview

- ❑ New Cnoidal Wave Theory
- ❑ Problem Unconventional Shale Gas at High Temperature and Pressure
- ❑ Cnoidal Wave Theory applied to Shale Gas
- ❑ Results

Recommendations for Shale Gas in Australia

# Mannhattan Project : Compressional (P)-shock Waves





# Hypothesis: compressional shock waves exist in the creeping flow regime. We will call them **Cnoidal Waves**

Assume as an example the Smectite-Illite (*S* →*I*) transition

$$2S + KFs \rightleftharpoons 2I + 4Qz(aq) + 9H_2O$$

$$S \rightarrow I, \quad \frac{dS}{dt} = Sk_0\, \mathrm{e}^{-\frac{E}{RT}}$$

The reaction releases large amount of fluids and the solid matrix compacts with a rate $k_0$ . Macroscopically this translates into a volumetric flow law $\dot{\varepsilon}_V$ where $\dot{\varepsilon}_0$ the rate constant $k_0$ becomes a strain rate constant

$$\dot{\varepsilon}_V = \dot{\varepsilon}_0 \left[ \frac{p'}{p'_n} \right]^m$$

# Cnoidal Waves ctd

The reaction is only possible if fluid flows, macroscopically this can be described by Darcy flow

$$\phi\overline{v} = -\frac{k}{\mu_f}\frac{\partial p_f}{\partial \xi} \Rightarrow \dot{\varepsilon}_V = \frac{k_\pi}{\mu_f}\frac{\partial^2 p_f}{\partial \xi^2}$$

$\overline{v}$ defines the fluid velocity (minus the solid velocity) in the direction of compaction $\chi$. The porosity is $\Phi$ and the permeability is $k$, $\mu_f$ is the fluid viscosity.

Substituting the power law for volumetric compaction and considering stress equilibrium in the direction of compaction gives

$$\frac{k}{\mu_f}\frac{\partial^2 p'}{\partial \xi^2} = \dot{\varepsilon}_0\left[\frac{p'}{p'_n}\right]^m$$

# Cnoidal Waves ctd

In order to understand the potential instabilities predicted by the solution of this PDE it is, useful to first consider McKenzie’s linear form of this equation power law exponent (*m=1*). In this case the diagenetic reaction would expel their fluids with a diffusive response in the compaction direction governed by a characteristic length introduced by McKenzie as compaction length

$$d_c = \sqrt{\frac{k m_s}{m_f}}$$

A coffee plunger is a good analogy. The compacting coffee powder expels fluids (the final coffee) with this diffusive length scale.

# Cnoidal Waves ctd

We now can consider cases where *m>1* and introduce following nondimensionalization

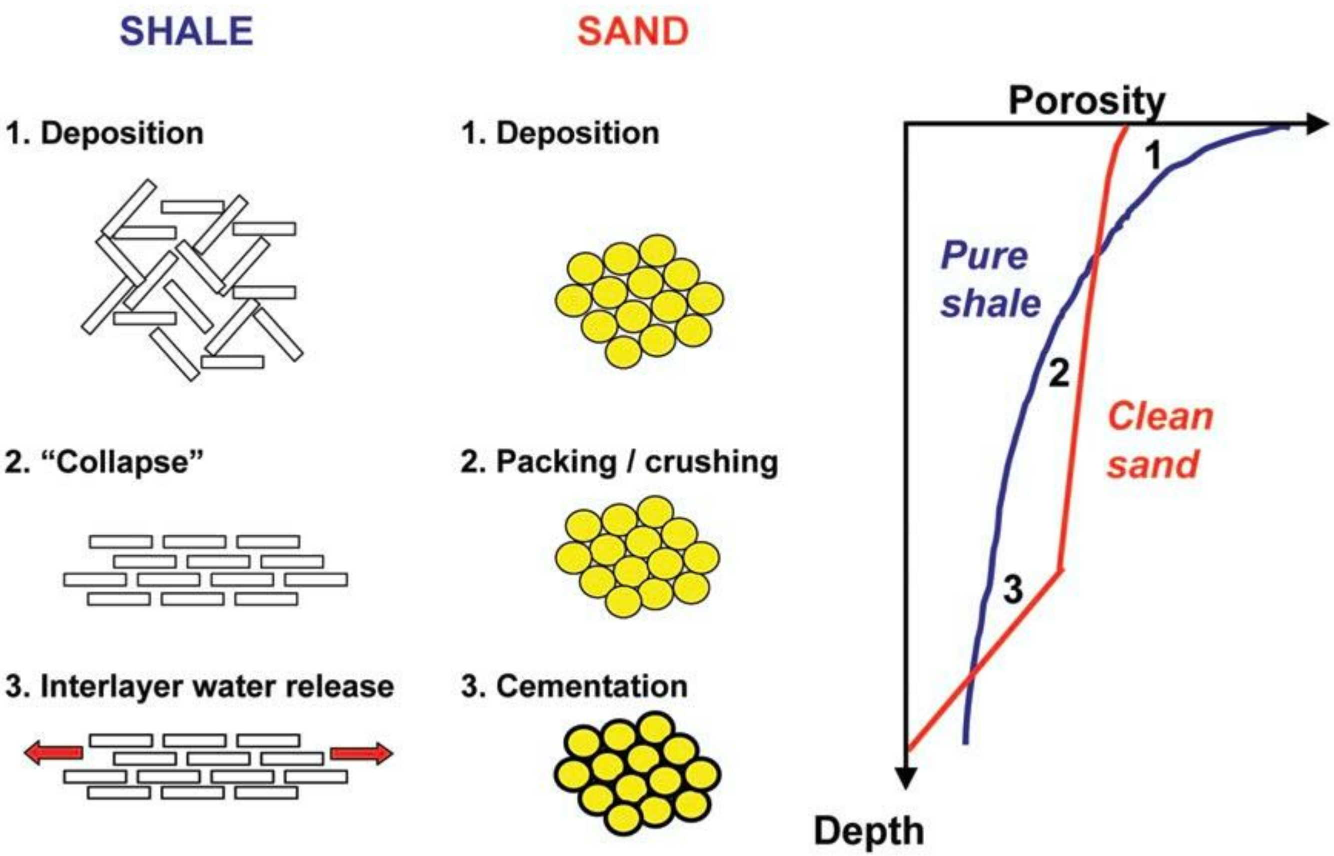
$$z = \frac{x}{H}, \qquad l = \left(\frac{H}{d_c}\right)^2, \qquad s = \frac{p'}{p'_n}$$

And obtain following PDE:

$$\frac{d^2 s}{dz^2} - l s^m = 0$$

This equation is also known as the Korteweg de Vries equation in shallow water theory. The solution for odd values of *m* are the Jacobi- (Cn) and for even values the Weierstrass (Sn) function (see Abramovitz and Stegun equation Eq. 18.9.11 (1964). This exact solution of a nonlinear periodic wave has much sharper crests than a sinus wave and is known as a **Cnoidal Wave**.

# Let us apply it to Diagenetic Release of Fluids in Shales




$$2S + KFs \rightleftharpoons 2I + 4Qz(aq) + 9H_2O$$

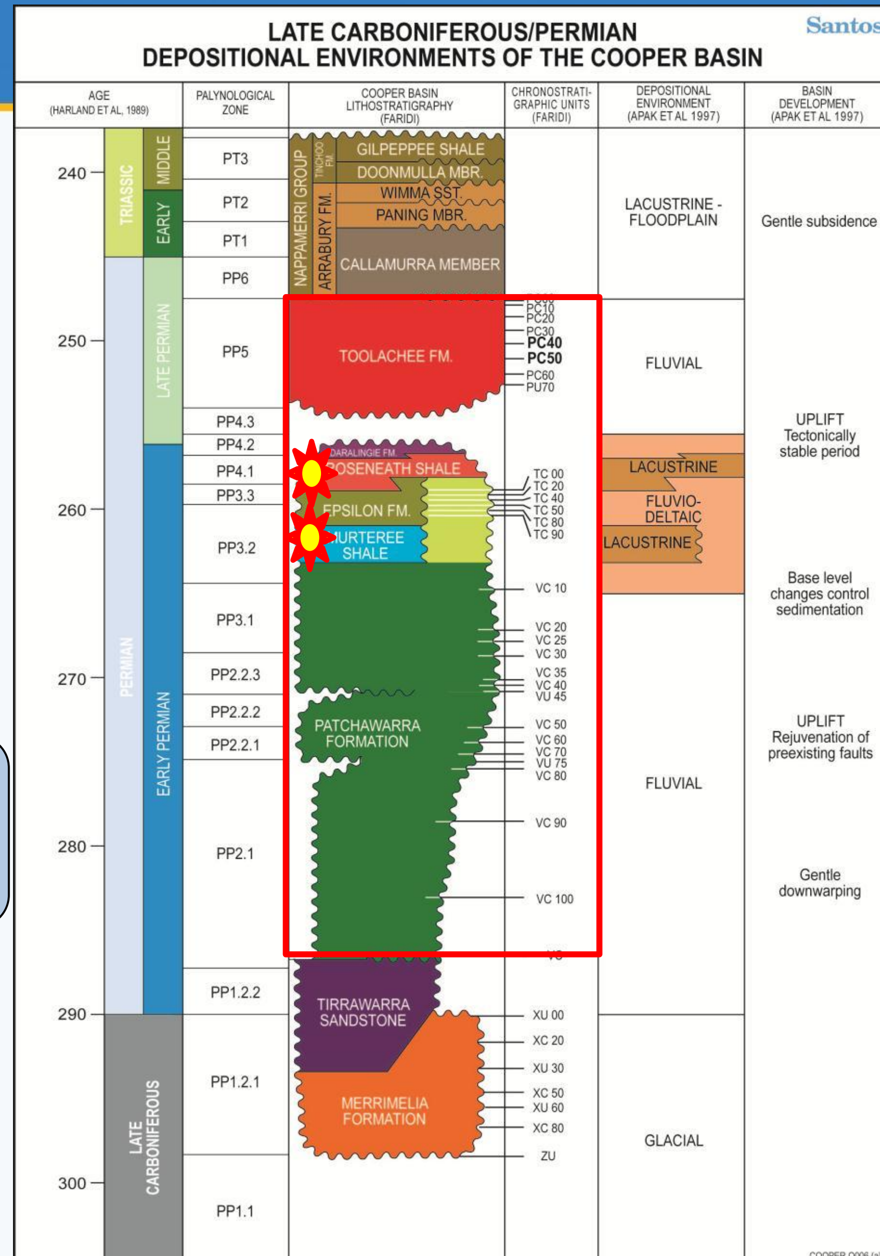
# Is the Moomba 191 success based on Cnoidal waves in shales?
# Initial flow rate 3 mmscf/d
# Current flow rate 2 mmscf/d


Santos operated Moomba gas processing plant, Cooper Basin

# Potential Cooper basin EARLY PERMIAN shale gas reservoirs

- Early Permian lacustrine mudrocks in the Roseneath and Murteree Shale formations
- shallow overfilled lacustrine basin setting
- "REM" Roseneath Epsilon Murteree Basin Centered Gas accumulation
- Present depth: 3500-4500 m
- Present temperature: ~200 C

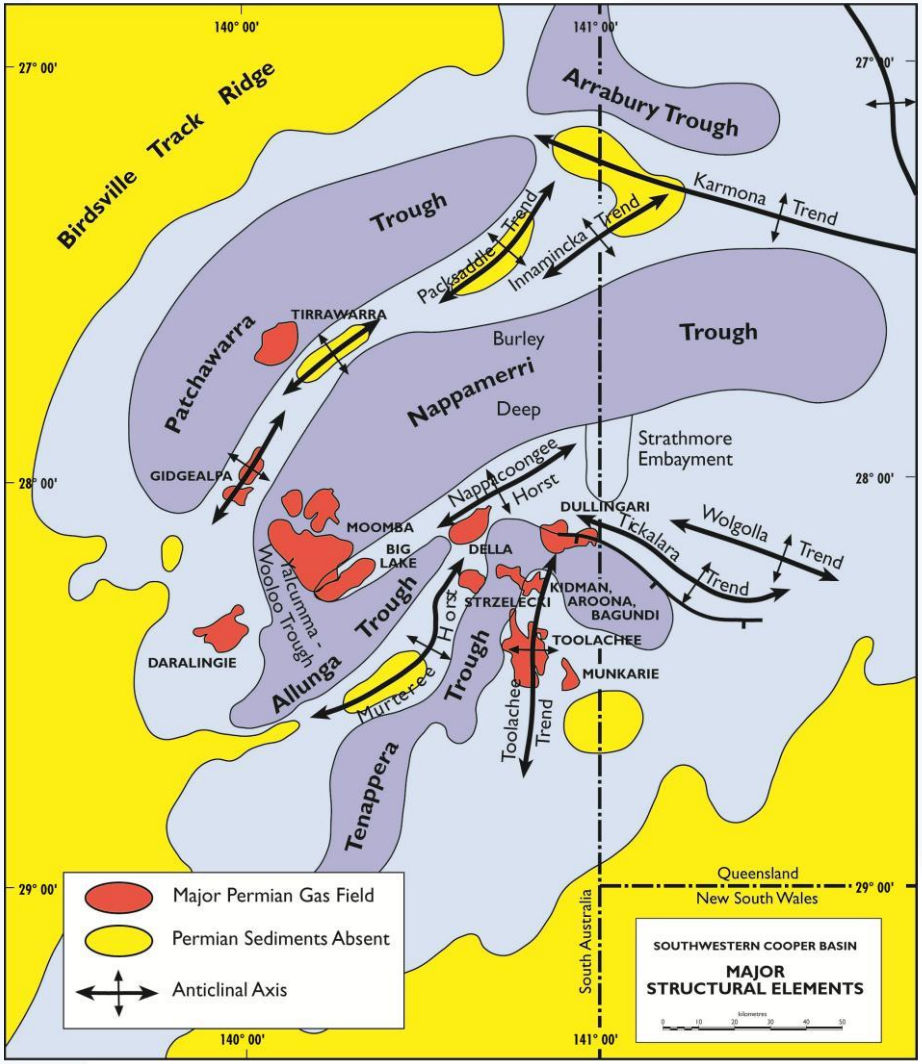
Higher temperature and higher pressures lead to a more ductile response




Santos
We have the energy.

# Variable controls on the Shale Gas potential of Cooper Basin lacustrine mudrocks

- Intracratonic basin with gas-prone Early Permian lacustrine mudrocks rather than marine oil-prone marine mudrocks
- Strong impact of diagenesis on the mineralogy (notably clays and siderite)
- High present day thermal gradient and overpressures at maximum burial depth influence the free (compression) gas storage capacity of these mudrocks
- Different Poroperm Network may be associated with inertinite dominated DOM and diagenetically altered clays
- In view of relatively low TOC the Inorganic derived porosity may be more important for free (compression) gas

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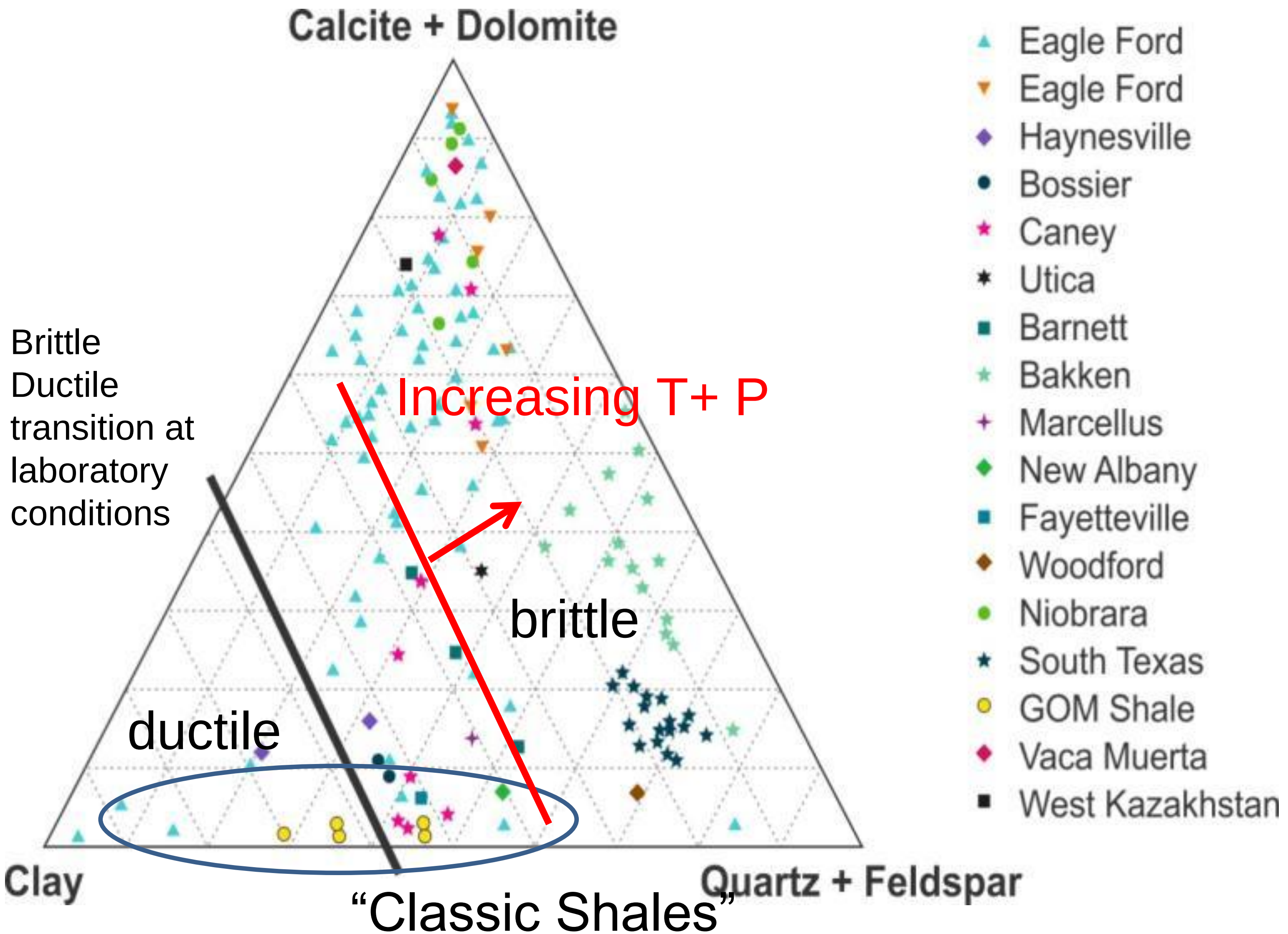
# Hi-T, Hi-P and Clay alteration



# For Ductile environment we expect quick Self healing of brittle fractures X-Ray CT in Boom Clay

Bernier& Bastiaens 2004 Selfrac Project

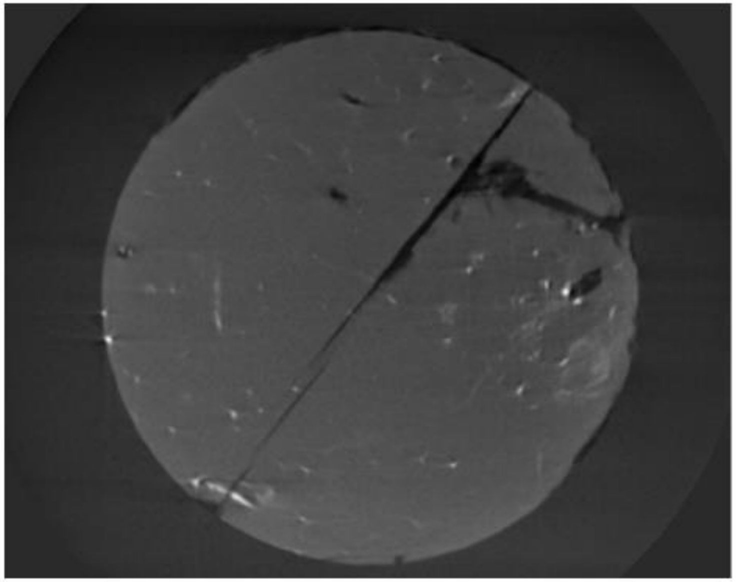


Figure 1a: Initial fracture within the sample

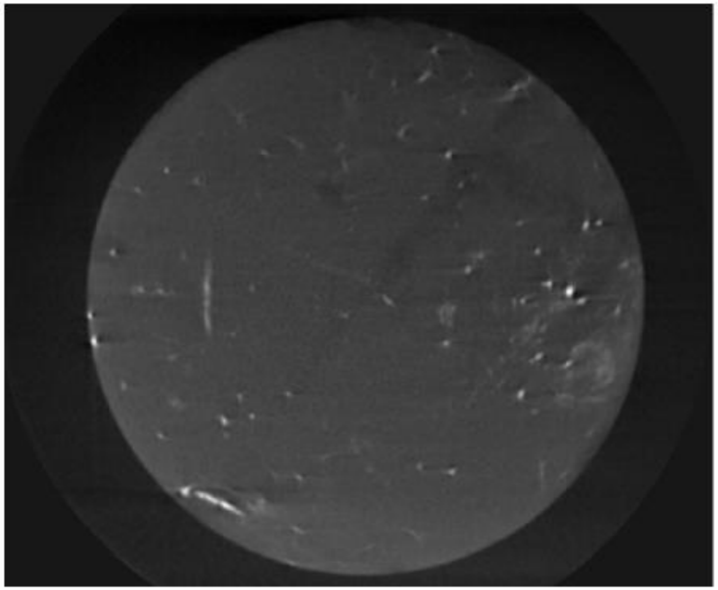


Figure 1b: Sealing after saturation o f the fracture

Santos Success based on ductile permeability generation

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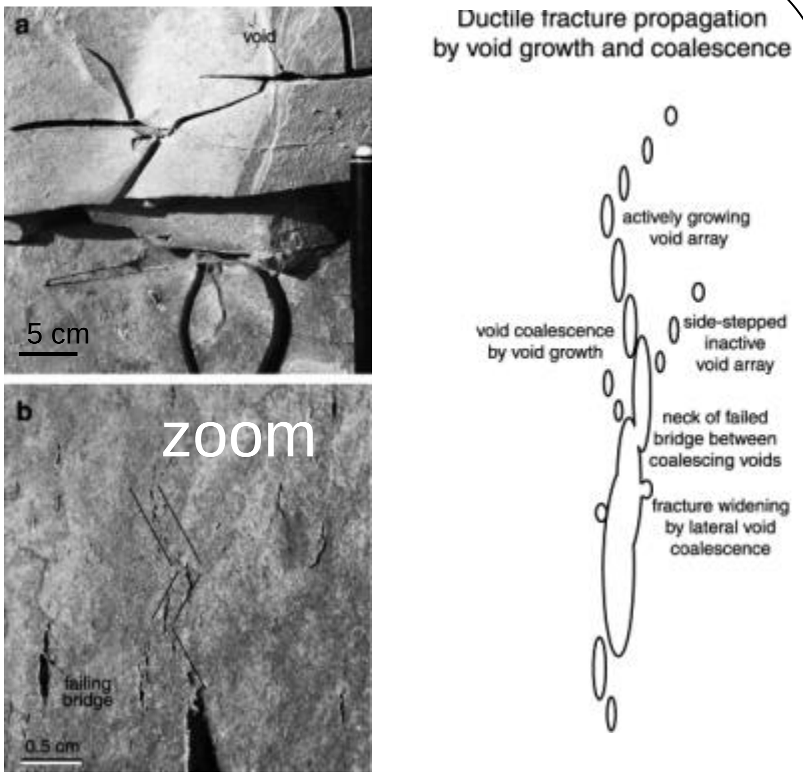
# Dilatant Ductile/Creep Fractures look like brittle fractures but they require creep around voids

Shales require similar stimulation strategies as deep geothermal projects, allowing us to deal with:

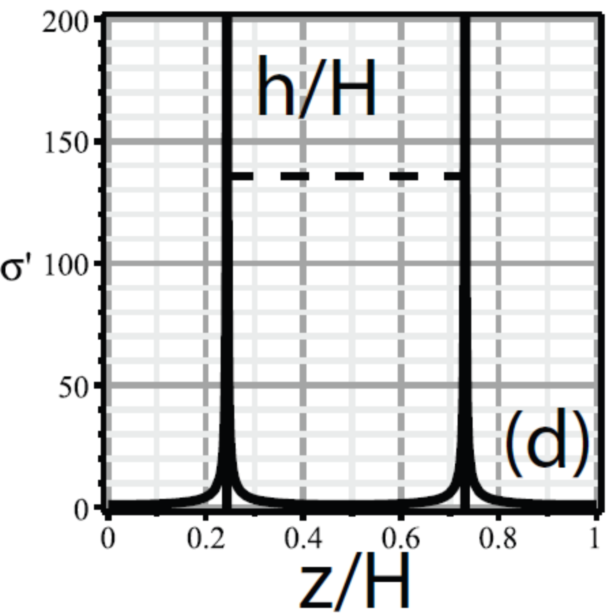
Multiphysics mixed brittle - ductile behaviour

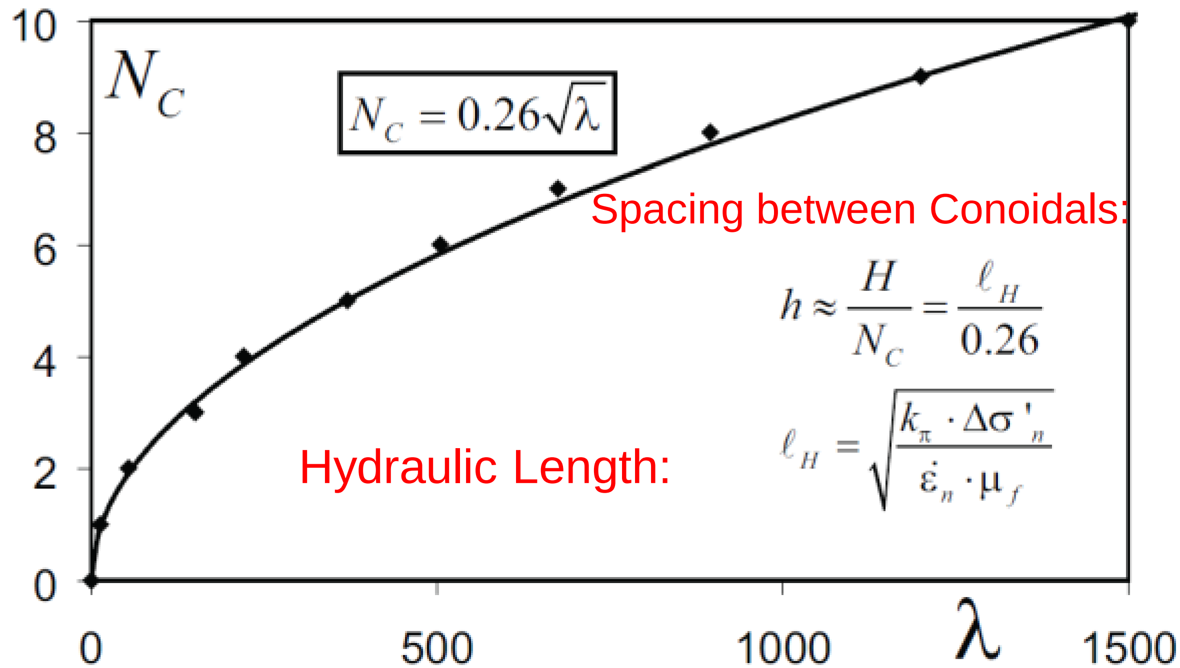
Ductile/creep fractures and ductile compaction bands



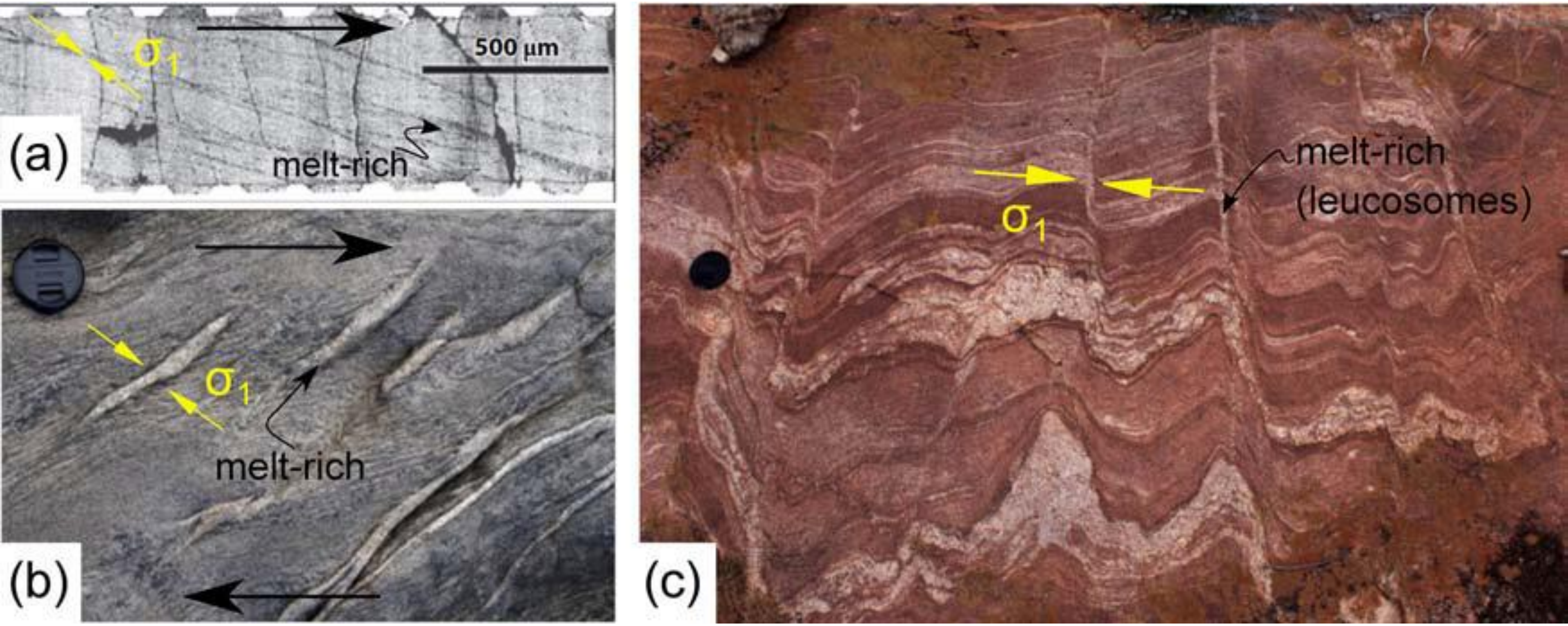

Eichubl and Aydin 2003

# Valley of Fire State Park Cnoidals?

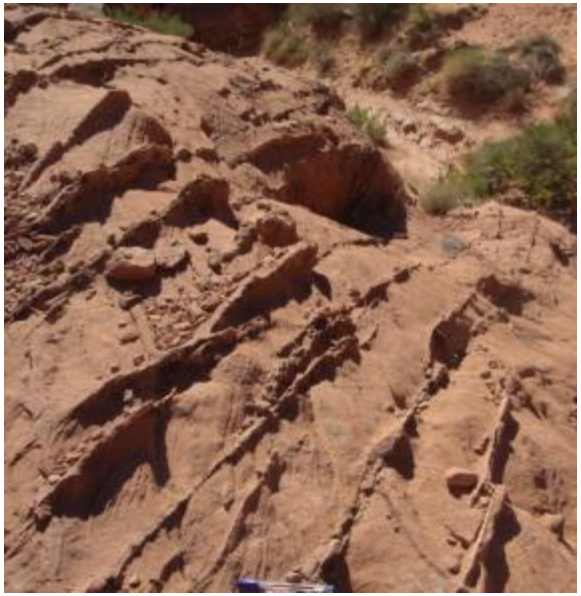



# Cnoidal Instabilities in Migmatites




Veveakis et al. Geophys. J. Int. (2015) 200, 519–523

# Other Cnoidals in laboratory and field scale



Aztec Sandstone
Chemenda 2009

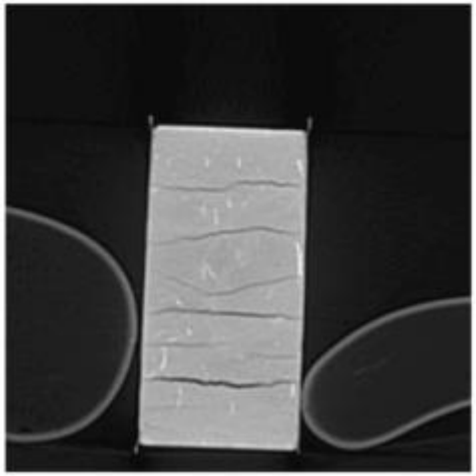


Fig. 4 CT-scan of a sample tested triaxially at 4.5 MPa confining pressure

Calcarenite
Baxevanis 2006

Ice
Harris 2009

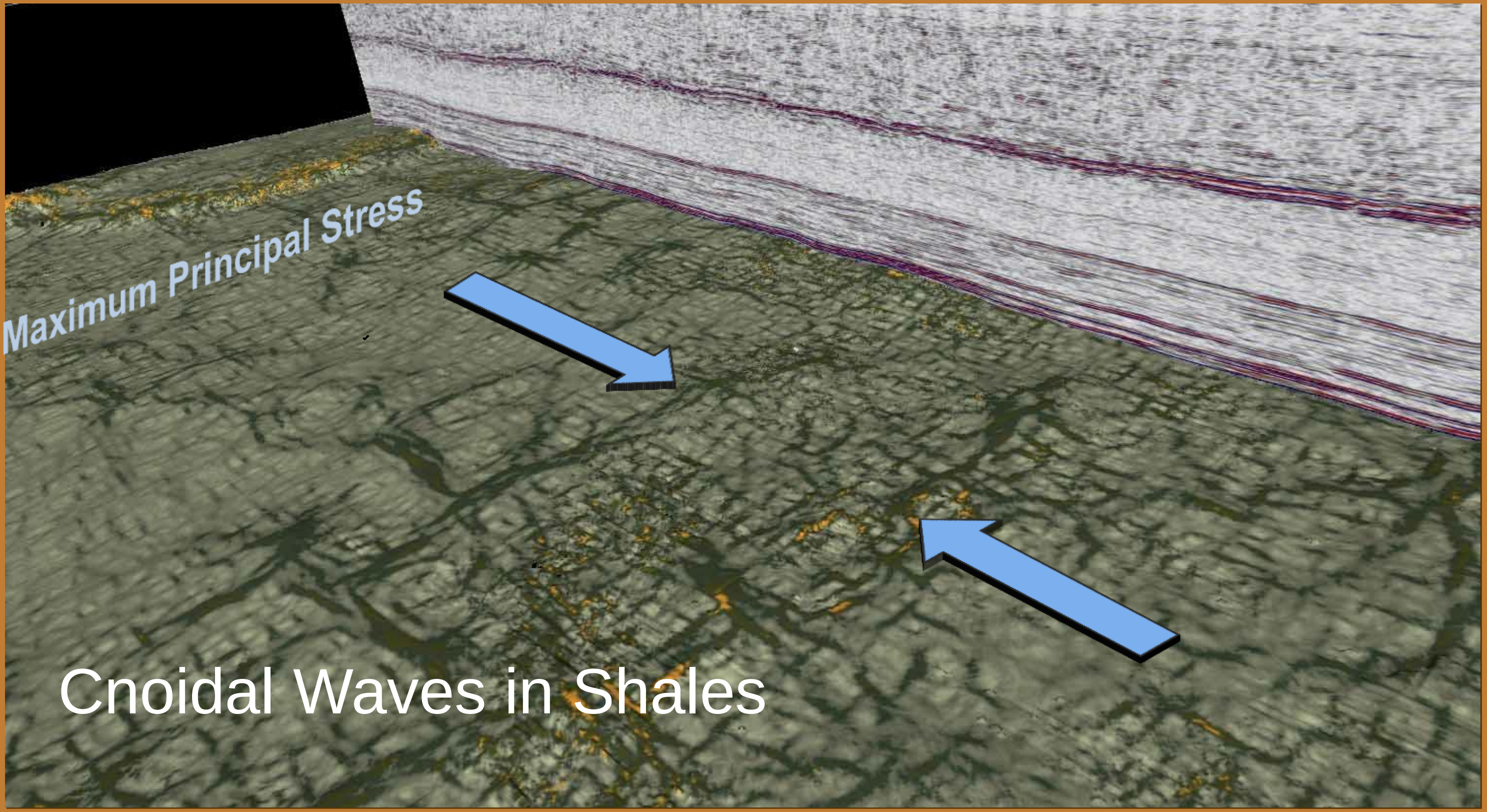
# Cnoidal orthogonal P-Waves in Solids: Compaction and Extension

US Army bombers flying over near-periodic swell in shallow water, close to the Panama coast (1933). The sharp crests and very flat troughs are characteristic for cnoidal waves

Crossing swells onsisting of near-cnoidal wave trains. Photo taken from Phares des Baleines (Whale Lighthouse) at the western point of Île de Ré (Isle of Rhé), France, in the Atlantic Ocean.

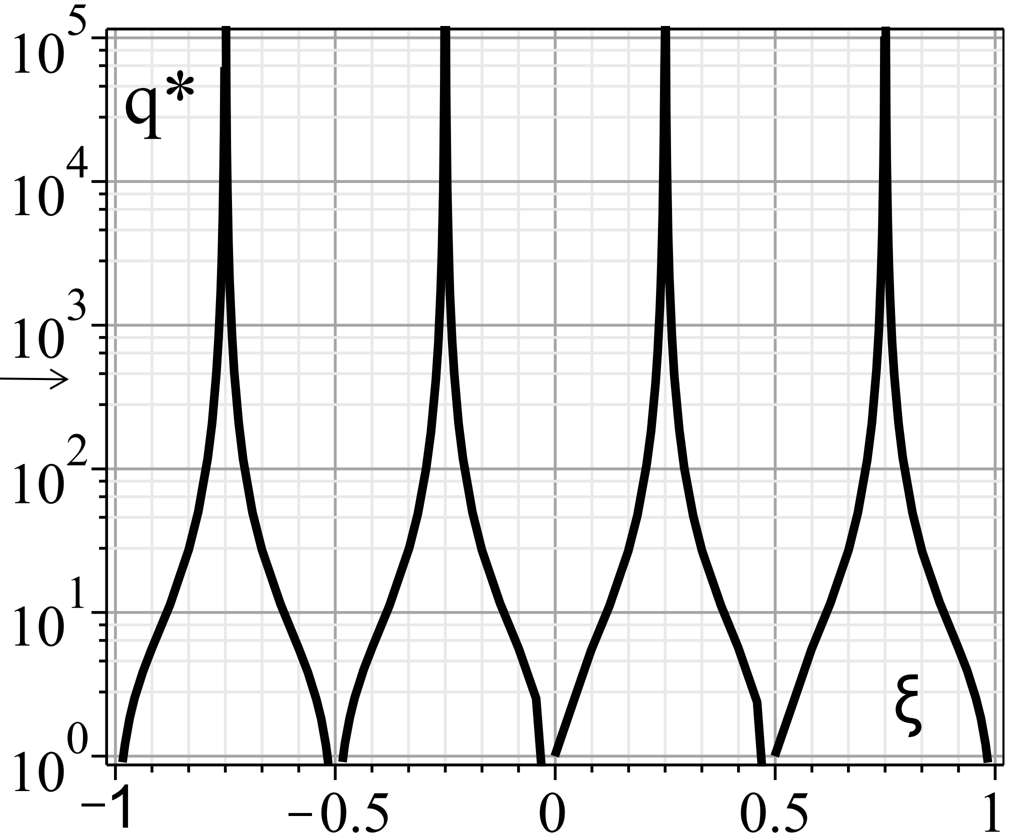
http://en.wikipedia.org/wiki/Cnoidal_wave

# Orthogonal N-S and E-W ductile pores along/ across present stress field at 3-4km depth




*Most positive curvature on Roseneath Shale horizon, Moomba-Big Lake 3D seismic cube (mapping and attribute analysis by Hani Abul Khair, supervisor Guillaume Backé).*

# Inside the ductile channels the gas flow rate is boosted by $10^5$ x Darcy's flow rate




$\sigma_1$

Critical fluid pressure required to sustain channel flow

$$p_f > \sigma_1 - \frac{\dot{\varepsilon}_1 \mu_f}{10\,k} L^2$$

Veveakis, Regenauer-Lieb and Weinberg GJI 2014

# Value proposition for Australian Shale Gas

1. Determination of critical fluid pressure required to sustain flow (much larger in Australia than the US)
2. Design smart reinjection procedure for CO2 to avoid reservoir pressure drop and fracture closing
3. Mobilise higher temperature gases/fluids from deeper units to sustain permeable pathways in shallower units
4. Smart directional drilling along or across DLB's
5. Use brittle-ductile stimulation protocol for reservoir enhancement
6. Use predicted spacing for further exploration

# Thanks from School of Petroleum Engineering

- Established in 1985 as a joint industry/UNSW initiative
- **Image based petrophysical rock properties** and EOR (ARC, Industry Consortium) - $500k/year
- **NMR Laboratory** (ARC, consortium) - $1mil in 2012; $200k/year since
- **CO2 sequestration** (CO2CRC) - $200k/year
- **Unconventionals** – CBM, Tight Gas, Shale Gas, Fractured Basement and Geothermal (ARC, DigitalCore, ONGC) - $2.2 mil in 2012 + $4.1 mil in 2014